

The Distance to Supernova 1998aq in NGC 3982

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ABSTRACT

The distance to NGC 3982, host galaxy to the Type Ia supernova SN 1998aq, is derived using 32 Cepheids discovered in archival multi-epoch *Hubble Space Telescope* observations. Employing recent Large Magellanic Cloud Cepheid period-luminosity relations and absolute zero point, we find a distance to NGC 3982 of 20.5 ± 0.8 (r) ± 1.7 (s) Mpc, including both random (r) and systematic (s) uncertainties, and ignoring any metallicity dependency in the Cepheid period-luminosity relation. Still unpublished light curve photometry promises to make SN 1998aq one of the most important calibrators for the Type Ia supernova decline rate–peak luminosity relationship.

Key words: Cepheids — distance scale — galaxies: distances and redshifts — galaxies: individual: NGC 3982 — supernovae: individual: SN 1998aq.

1 INTRODUCTION

Corrected for the shape of their light curves, and calibrated via Cepheid distances to their host galaxies, the peak luminosities of Type Ia supernovae (SNe) provide excellent standard candles for studying the extragalactic distance scale. Their extremely high peak luminosities coupled with small intrinsic scatter lead to Type Ia SNe being recognised as perhaps the most powerful of available tools for deriving the Hubble Constant (e.g., Phillips et al. 1999; Riess et al. 1999; Jha et al. 1999; Gibson et al. 2000; Saha et al. 2001; Freedman et al. 2001; Gibson & Stetson 2001; Gibson & Brook 2001).

Cepheid distances to ten Type Ia SN-host galaxies are now available in the literature — NGC 4414 (Turner et al. 1998), NGC 3368 (Tanvir et al. 1999), NGC 2841 (Garnavich et al. 2001), and seven from the Saha et al. (2001, and references therein) Type Ia SN *Hubble Space Telescope* (HST) Calibration Project (IC 4182, NGC 5253, 4536, 4496A, 4639, 3627, and 4527). Calibrating the corrected peak luminosities of the respective SNe resident in each of these galaxies, and employing the Calán-Tololo and CfA Type Ia SN Hubble Diagrams to derive the Hubble Constant H_0 , yields $H_0 = 72 \pm 2$ (r) ± 7 (s) $\text{km s}^{-1} \text{Mpc}^{-1}$ — including both total random (r) and systematic (s) uncertainties — e.g. Gibson & Stetson (2001). An eighth galaxy observed as part of the Saha et al. program, NGC 3982, is host to the prototypical Type Ia supernova SN 1998aq. Of all the calibrators discussed to date, SN 1998aq has perhaps the highest quality,

in terms of multiwavelength photometric precision and light-curve coverage (see Table 1 of Gibson et al. 2000).

SN 1998aq was discovered on 1998 April 13, by Mark Armstrong (Hurst et al. 1998), as part of the U.K. Nova/Supernova Patrol. The host galaxy, NGC 3982, is a Seyfert-2 SAB(r)b: spiral, and a possible^{*} member of the Ursa Major Cluster of galaxies. Armstrong's discovery took place approximately two weeks before the supernova reached its *B*-band maximum. Exquisite multi-colour photometry spanning the rise and fall of the supernova light curve was subsequently collected by at least one team, but at the time of submission of this manuscript the data had not yet been made public. As a result, the incorporation of SN 1998aq into the Type Ia SN calibration zero point is necessarily reserved for a future paper. Until then, we make available to the community our new Cepheid-based distance determination to the host galaxy, NGC 3982.

2 ANALYSIS

NGC 3982 was observed with the Wide Field Planetary Camera 2 (WFPC2) at 17 epochs over the 53-day window spanning 2000 March 20 – May 12. Cosmic-ray split 2500 s exposures in F555W (V; 12 epochs) and F814W (I; 5 epochs) were taken. As noted earlier, this galaxy is the eighth to be observed as part of the Saha et al. Type Ia SN Calibration

^{*} Its membership has been questioned by some (e.g., Tully et al. 1996).

Project (*HST* PID 8100; Saha et al. 2001, and references therein).

Data processing followed the precepts outlined in Gibson & Stetson (2001, and references therein). Instrumental photometry was provided by ALLFRAME (Stetson 1994), while a version of TRIAL (Stetson 1996) — customized for WFPC2 data and the fitting of Cepheid light curves in the *V* and *I* photometric bands — was used for calibration and variable finding. A slightly refined version of the Stetson (1998) WFPC2 photometric zero points and charge transfer corrections were employed, as was done in Freedman et al. (2001), Gibson & Stetson (2001), and Gibson & Brook (2001). Our quoted systematic error budget includes a ± 0.07 mag component that allows for the uncertainties associated with our current understanding of the spatial and temporal properties of the WFPC2 charge-transfer inefficiencies.

Candidate variables returned by TRIAL were culled to a final set of 32 high-quality Cepheids. The criteria employed in this selection were as follows:

- modified Welch & Stetson (1993) index > 0.60
- variable has data from a minimum of ten frame-pairs
- mean *V*-magnitude $\langle V \rangle$ fainter than 24.4 mag
- mean colour $0.40 < (\langle V \rangle - \langle I \rangle) < 1.40$
- period > 10 days
- semi-amplitude of fundamental harmonic > 0.22 mag
- visual inspection of image
- visual inspection of lightcurve

A selection on the ALLFRAME image-quality index χ was considered, but the stars meeting the above eight criteria were found to be completely normal in their χ values. The properties of the 32 Cepheids passing this selection are listed in Table 1. Epoch-by-epoch photometry for each of the Cepheids, local calibration standards, and accompanying light curves have been made available at our *HST* Cepheid archive.[†]

Figure 1 shows the apparent *V*- and *I*-band period-luminosity (PL) relations for the 32 Cepheids in NGC 3982 (upper and middle panels, respectively). Figure 2 shows the positions of these Cepheids in the calibrated (*V*, *V*−*I*) colour-magnitude diagram. After Freedman et al. (2001), the apparent moduli of Figure 1, coupled with the assumption of a standard reddening law, Large Magellanic Cloud (LMC) absolute distance modulus $\mu_0(\text{LMC}) = 18.50 \pm 0.10$ mag, and the new OGLE LMC apparent PL relations (Udalski et al. 1999), yield the distribution of dereddened true moduli μ_0 shown in the bottom panel of Figure 1. The unweighted mean true modulus, based upon all 32 Cepheids, is $\langle \mu_0 \rangle = 31.559 \pm 0.081$ (*r*), where the total random uncertainty (*r*) includes components due to photometry, extinction, and dereddened PL fit, added in quadrature (corresponding to R_{PL} in Table 7 of Gibson et al. 2000).[‡] It is re-

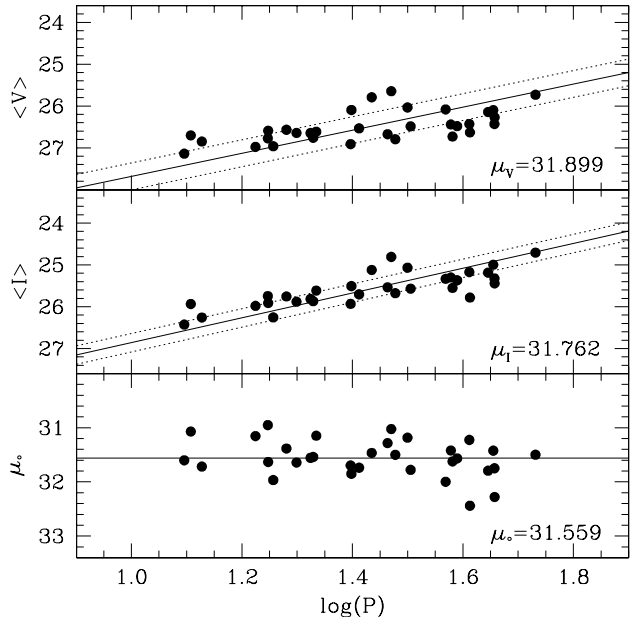


Figure 1. Apparent period-luminosity relations in the *V*- (upper panel) and *I*-bands (middle panel) based upon the 32 Cepheids discovered in NGC 3982 (the properties of which are listed in Table 1). The solid lines are least-squares fits to this entire sample, with the slope fixed to be that of the Udalski et al. (1999) LMC PL relations, while the dotted lines represent their corresponding $\pm 2\sigma$ dispersion - reflecting the width of the LMC instability strip. The inferred apparent distance moduli, ignoring metallicity effects, are then $\mu_V = 31.899 \pm 0.070$ (internal) and $\mu_I = 31.762 \pm 0.056$ (internal). Lower Panel: Distribution of individually de-reddened Cepheid true moduli, as a function of period. The mean corresponds to $\langle \mu_0 \rangle = 31.559 \pm 0.081$ (random).

assuring that the *median* of the distribution (31.594) agrees with the *mean* (31.559).

Our quoted result — $\langle \mu_0 \rangle = 31.559 \pm 0.081$ (*r*) — inherently assumes that the Cepheid PL relation is independent of metallicity (i.e., $\gamma_{\text{VI}} = 0.0$ mag dex^{−1}). If one assumes a metallicity dependence of the form $\gamma_{\text{VI}} = -0.2$ mag dex^{−1} (Freedman et al. 2001), though, a measure of the mean metallicity for the WFPC2 Cepheid field is required to determine the true metallicity-corrected distance modulus μ_Z . Unfortunately, no HII regions in this field have thus far been observed. Adopting a conservative metallicity range of $12 + \log(\text{O}/\text{H}) = 8.9 \pm 0.4$ (as we did for the analysis of the NGC 4527 dataset — Gibson & Stetson 2001) would increase the inferred mean true modulus by ~ 0.08 mag.

The mean reddening inferred from the 32 Cepheids is $E(V-I) = 0.138 \pm 0.029$ mag (internal), of which only ~ 0.019 mag is due to foreground Galactic extinction (Schlegel et al. 1998). While it might be tempting to assign a field mean metallicity based upon an assumed *intrinsic* relationship between $E(V-I)$ and $12 + \log(\text{O}/\text{H})$, unfortunately — as already noted in Gibson & Stetson (2001) — for $0.1 \lesssim E(V-I) \lesssim 0.3$ (a regime which the NGC 3982 Cepheids inhabit), there is no trend seen in the data, with metallic-

man et al. 2001) does not afflict our NGC 3982 dataset, and so we employ the full set of 32 Cepheids in our quoted final result.

[†] See <http://astronomy.swin.edu.au/bgibson/H0kp>.

[‡] Enforcing a lower period cut of 25 days reduces the Cepheid sample from 32 to 20, the unweighted mean true modulus for which is $\langle \mu_0 \rangle = 31.626 \pm 0.096$ (*r*), consistent with our favoured result of $\langle \mu_0 \rangle = 31.559 \pm 0.081$ (*r*). This suggests that PL bias of the magnitude encountered for *some* galaxies (see § 3.4 of Freed-

Table 1. Properties of Cepheids detected in NGC 3982.

ID	Chip	X ^a	Y ^a	<V>	<I>	P	μ ₀
C01	1	240.3	245.6	26.98±0.04	25.98±0.07	16.77±0.21	31.15
C02	1	674.2	89.2	26.76±0.04	25.87±0.07	21.33±0.24	31.54
C03	2	125.2	319.8	26.08±0.03	25.33±0.06	37.05±1.59	32.00
C04	2	153.1	314.1	25.73±0.03	24.71±0.04	53.87±2.85	31.50
C05	2	177.9	496.6	26.53±0.05	25.70±0.08	25.83±0.59	31.74
C06	2	197.7	467.2	26.27±0.03	25.44±0.03	45.44±2.73	32.28
C07	2	220.0	742.7	26.49±0.04	25.57±0.06	32.02±1.03	31.78
C08	2	354.8	484.0	26.96±0.06	26.26±0.06	18.06±0.27	31.97
C09	2	356.4	691.9	26.64±0.03	25.88±0.06	19.90±0.30	31.64
C10	2	441.4	411.3	26.63±0.04	25.78±0.05	41.00±1.71	32.44
C11	2	463.2	-4.2	26.59±0.04	25.91±0.07	17.68±0.67	31.63
C12	2	471.9	32.7	27.14±0.05	26.43±0.18	12.47±0.34	31.60
C13	2	503.7	33.8	26.70±0.03	25.94±0.05	12.81±0.19	31.07
C14	2	504.4	287.4	26.67±0.05	25.54±0.06	29.08±1.84	31.28
C15	2	551.4	-25.1	26.91±0.03	25.93±0.05	24.94±1.16	31.70
C16	2	578.5	390.6	26.73±0.03	25.55±0.05	38.12±0.59	31.62
C17	2	613.2	392.8	26.85±0.04	26.26±0.07	13.41±0.22	31.72
C18	3	245.7	504.8	26.04±0.04	25.07±0.05	31.60±1.25	31.18
C19	3	446.1	463.9	25.79±0.02	25.12±0.04	27.23±0.88	31.47
C20	3	446.4	591.2	26.10±0.04	25.51±0.07	25.01±1.38	31.85
C21	3	701.3	-1.6	26.80±0.05	25.68±0.06	30.04±2.92	31.50
C22	4	137.7	145.1	26.10±0.04	25.00±0.04	45.18±2.75	31.42
C23	4	192.5	200.0	26.61±0.04	25.61±0.06	21.61±0.68	31.15
C24	4	215.8	402.2	26.44±0.03	25.30±0.04	37.86±1.11	31.42
C25	4	227.3	316.8	26.77±0.04	25.75±0.05	17.66±0.39	30.95
C26	4	278.8	193.4	26.48±0.05	25.37±0.06	38.87±1.02	31.57
C27	4	297.2	272.5	26.65±0.03	25.81±0.06	21.09±0.50	31.56
C28	4	324.9	201.4	26.57±0.05	25.75±0.06	19.08±0.57	31.38
C29	4	417.8	277.9	26.43±0.05	25.17±0.05	40.89±1.18	31.23
C30	4	487.3	213.7	26.14±0.03	25.19±0.04	44.22±1.38	31.79
C31	4	505.6	14.8	26.43±0.04	25.32±0.06	45.41±3.94	31.75
C32	4	562.8	50.3	25.65±0.02	24.81±0.03	29.53±0.88	31.02

^a Pixel coordinates are references with respect to *HST* archive image u5ky0101r.

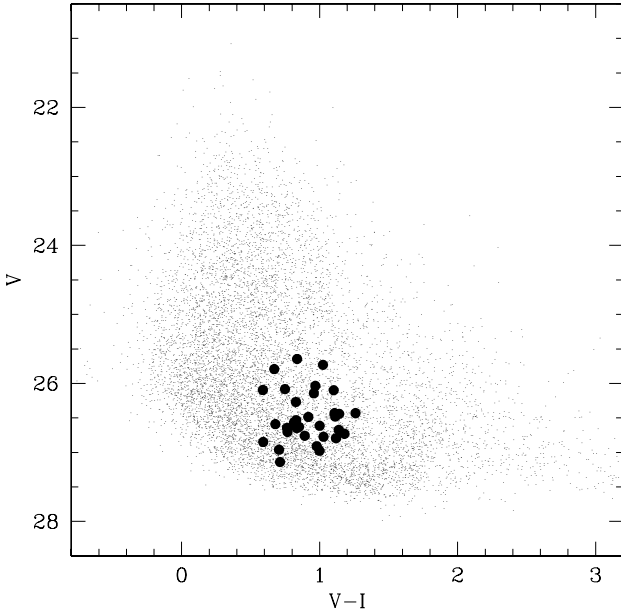


Figure 2. Calibrated NGC 3982 colour-magnitude diagram. The filled circles correspond to the 32 Cepheids of Table 1.

ities $8.50 \lesssim 12 + \log(\text{O}/\text{H}) \lesssim 9.35$ equally likely. The *true* intrinsic extinction in the vicinity of SN 1998aq (as opposed to assuming that the reddening appropriate to the mean Cepheid necessarily applies to SN 1998aq) will only become apparent once the full multi-colour photometry of the supernova becomes available.

While its membership in the Ursa Major Cluster has not been established unequivocally (Tully et al. 1996), it is perhaps telling that an independent Tully-Fisher analysis leads to a mean cluster distance modulus of 31.48 mag (Freedman et al. 2001). This latter value is consistent with our new SN 1998aq distance — 31.559 ± 0.081 (*r*) mag.

Without access to calibrated multicolour photometry (or Cepheids), Vinkó et al. (1999) attempted to infer a distance to SN 1998aq using the Riess et al. (1999) ‘snapshot technique’. Because of the lack of data available at the time, deriving an accurate value of the reddening along the line of sight was a near impossibility. This uncertainty in the extinction is responsible for an equal uncertainty in their SN 1998aq distance determination of 30.89 ± 0.56 mag. Vinkó et al. stress that the true modulus is probably greater than their quoted value. Regardless, the original Vinkó et al. value is consistent with our improved result, at the $\sim 1.2\sigma$ level.

We have not yet mentioned the systematic error budget. After Gibson & Brook (2001; Table 2) and Freedman et al. (2001), seven sources of systematic uncertainty in the Hub-

ble constant are considered significant, including the LMC zero point, crowding, large scale bulk flows, the metallicity dependence of the Cepheid PL relation, the WFPC2 zero points, Cepheid reddening values, and bias in the PL relation. In determining the distance to an individual galaxy, all these error sources are equally applicable *except* the possibility of large-scale bulk flows. In quadrature, the remaining systematic error budget (s) amounts to 0.179 mag. In combination with the already stated total random error budget, our final value for the distance to SN 1998aq in NGC 3982 is

$$< \mu_0 > = 31.559 \pm 0.081 (r) \pm 0.179 (s) \text{ mag},$$

assuming that a zero slope is the best available estimate for the metallicity dependence of the Cepheid PL relation — i.e., $d=20.5\pm0.8 (r)\pm1.7 (s)$ Mpc. If the slope of the metallicity dependence is in fact $-0.2 \text{ mag dex}^{-1}$, the modulus is increased by ~ 0.08 mag for reasonable assumptions about the metallicity of young stars in NGC 3982.

3 SUMMARY

A Cepheid-based distance to NGC 3982, host to supernova SN 1998aq, has been derived using the same software pipeline and variable-finding algorithms employed throughout the *HST* Key Project on the Extragalactic Distance Scale. Ignoring any potential metallicity dependence in the Cepheid period-luminosity relation (expected to be on the order of 4% for NGC 3982), we determine a distance to the supernova (and galaxy) of $20.5\pm0.8 (r)\pm1.7 (s)$ Mpc. Our result is consistent with the Tully-Fisher distance to the Ursa Major Cluster (19.8 Mpc), suggesting that NGC 3982 is indeed a cluster member. Still unpublished multi-colour light curve photometry promises to make SN 1998aq one of the most important calibrators for the extragalactic distance scale.

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Note added in proof: After submission, a preprint from Saha et al. (2001, ApJ, submitted, astro-ph/0107391) appeared which quotes an NGC 3982 distance modulus of $\mu_0=31.72\pm0.14$, based upon an independent DoPHOT and HSTphot analysis of the data described herein. The distance found by our ALLFRAME+TRIAL analysis - $31.56\pm0.08 (r)\pm0.18 (s)$ - is tied to the Udalski et al. (1999) LMC PL relations, while the Saha et al. result is based upon those of Madore & Freedman (1991, PASP, 103, 933). As discussed in Freedman et al. (2001) however, the former are to be preferred over the latter. Regardless, if we were to adopt the Madore & Freedman relations, our inferred NGC 3982 distance modulus would become $31.73\pm0.08 (r)\pm0.18 (s)$, indistinguishable from that of Saha et al.

Despite these near-identical true distance moduli, there are differences in the analyses - our apparent V - and I -band moduli are 0.13 mag and 0.07 mag smaller than those of Saha et al. - these differences are ameliorated by the inferred reddening $E(V-I)$, ours being 0.06 mag lower than that of Saha et al ($E(V-I)=0.05$ versus 0.11, for the same Madore & Freedman 1981 LMC PL relations).

A detailed comparison of the photometric differences between the two analyses will have to wait until standard star photometry from the Saha et al. group becomes available. It should be noted though that such Cepheid photometry differences are not uncommon (Gibson et al. 2000; Table 3).